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Aspects of the interplay between physics and biology*

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The interplay and exchanges between physics and biology form a very fascinating field of study, to which many distinguished persons have contributed. In the material to follow, my aim is not so much to present new physics to the physicists or new biology to the biologists, but rather to present to each some interesting thoughts and provocative points of view from the other's field. This may enhance one's appreciation and understanding of the entire situation. On the technical side, I beg to be excused for any errors I may commit in speaking of aspects of biology, and I hope not to commit any in dealing with physics.

Right away one might contrast physics and biology in quite strong terms as follows. While the aim of physics is to find and describe universally valid laws governing processes and phenomena everywhere in the universe, the biologist is concerned with the very singular and unusual single occurrence of life on earth and, for practical purposes, on earth alone. To a certain extent, he is like a detective or archaeologist searching for clues about past developments and events in building up a picture of life and evolution as a whole. This basic contrast may well be kept in mind—the contrast between the universal and the particular—despite the fact that within life itself in all its forms there are many universal features. Another interesting contrast is that in our understanding and interpretation of biological processes, the ideas of a suitably defined *value* for each process and its *consequences* both play extremely important roles, in ways that are quite inappropriate in the context of physics.

Let me begin by briefly recounting some of the major developments in physics, more especially classical physics. Physics in the modern sense started with the work of Galileo and Newton, and especially their demonstration that carefully controlled experiments, with the results expressed in mathematical terms, could lead to deep and dependable understanding of the laws underlying natural phenomena. In this way one could pass from precise description to explanation, then to prediction and on to verification. Galileo took the first steps in discovering the fundamental principles of motion, in the process overhauling the older, more naive Aristotelian views of mechanics. Galileo's results were synthesized and added to by Newton, and set out in axiomatic form. Newton also discovered the universal law of gravitation, the first example of a unification in physics, and gave a common explanation for celestial and terrestrial gravitational phenomena.

These achievements of Galileo and Newton set the programme for natural science for the succeeding centuries—quantification by measurement, and mathematical analysis. Newton's own work was a combination of inductive and deductive methods,

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in that after the laws of inertia and motion had been gradually discovered through ingenious experiments and arguments, he set them up as an axiomatic system from which consequences could be derived using mathematics and logic alone. He also gave clear expression to definite views on the nature of space and time: the absoluteness of each, their mutual independence, the validity of Euclidean geometry of space, and the uniform flow of time. In all this he was greatly influenced by the style of geometry which Euclid had crystallized in his *Elements*. Indeed, Newton preferred geometrical arguments to algebraic analytical ones in deducing consequences from the axioms. Geometry in turn, from Greek times, had acquired the status of being a product of pure reason and intellect, which nature had to necessarily obey. The greatest exponent of this philosophy was of course Plato.

During the eighteenth century, with the efforts of many mathematical physicists, the domain of validity of Galilean–Newtonian physics was much extended, and many successes achieved. Apart from the continuing applications to astronomy, the theories of continuous media, fluid dynamics, elasticity, etc. were initiated by Euler, Lagrange, Cauchy and others. In celestial mechanics itself, it culminated in the monumental works of Laplace and Lagrange on the subject. By the end of the eighteenth century, some understanding had been achieved in the twin fields of electricity and magnetism as well, and everything seemed accessible to and falling into the Galilean–Newtonian pattern. Against a fixed space–time background, all processes were describable in a causal and deterministic way; and the universe ran itself like a giant machine.

To a certain extent, all this advance was possible by separating natural science from philosophical preconceptions and prejudices, and, so to say, allowing the phenomena to speak for themselves and listening carefully and imaginatively. In the words of Max Born, speaking of Galileo and Newton, 'The distinctive quality of these great thinkers was their ability to free themselves from the metaphysical traditions of their time and to express the results of observations and experiments in a new mathematical language regardless of any philosophical preconceptions.' But one cannot deny the fact that, nevertheless, these developments became possible thanks to a liberating philosophical atmosphere in the background, to which Bacon, Leibnitz, Descartes, Spinoza and others all contributed in one way or another. There were in fact two main schools of thought, the continental rationalist school (to which Descartes, Leibnitz and Spinoza belonged, notwithstanding differences in their views) and the English empiricist school of Locke, Berkeley and Hume. Stated simply and in a single sentence, the rationalist philosophers clung to the idea, going back to Plato, that reason was superior to and controlled experience, while the empiricists believed, as a kind of reaction, that everything had to be learned from experience alone. A kind of compromise or reconciliation of the two, and at the same time an explanation of the tremendous successes of Galilean–Newtonian physics, was attempted by Immanuel Kant towards the end of the eighteenth century. He distinguished between analytic and synthetic statements on the one hand, and between a priori and non-a-priori truths on the other. An analytic statement is a statement based on pure logic alone, the contrary to which cannot even be imagined, and in that sense it is empty as it cannot but be true. For example, definitions are analytic statements. A synthetic statement is one that has nontrivial content, a positive assertion, the opposite of which can in principle be at least imagined. Thus a synthetic statement is not a purely logical statement.

Knowledge drawn from experience is of the synthetic kind but in principle there could be other sources of synthetic knowledge. A priori truths are truths not based on experience, truths possibly logically derived from some basic starting points, which in their turn are not based on experience. Non-a-priori truths then are truths derived from experience.

Kant tried to combine rationalist and empiricist points of view in a scheme ultimately intended to justify the successes of Galilean–Newtonian physics. He viewed knowledge as partly drawn from experience and partly a priori; what he sought was absolutely certain and dependable knowledge, which necessarily had to apply to the world of experience. He was thus seeking for *synthetic*, non-empty truths or knowledge that had *necessarily* to apply to actual experience but could not be *derived* from it. This was the strategy to his *explaining* the success of Galilean–Newtonian physics. Such knowledge was called by him the *synthetic a priori*: non-empty truths present in advance of experience. To achieve his goal, Kant made some of the fundamental principles of Galilean–Newtonian science (which were actually the distilled statements of experiments and experience) synthetic a priori's. These included the nature of space and time, the validity of Euclidean geometry, causality and determinism.

Kant's idea was that the synthetic a priori's are a presupposition or precondition for science, not a result of scientific discovery. Thus all the sensations and experiences of the external world incident upon us are seen through the glasses or pass through the filters of Newtonian absolute space and time, Euclidean geometry, strict causality, etc. On all that comes to us from the outside, the mind imposes these categories; we have no other way of handling experience. Since science presupposes all these, we explain why these principles work by saying that nature could not be otherwise. More properly, one might say we are incapable of viewing nature in any other way. In later formulations, Kant included some of the detailed features of Newton's dynamics, such as the law of equality of action and reaction, and the law of conservation of mass, among the synthetic a priori's. Basically, the empirical successes of Galilean–Newtonian physics were made inevitable features of experience. Even if nature were different, we would never know, because our minds would always interpose these synthetic a priori's immediately upon all incoming sensory experience, and meaning and interpretation would only come later. In a way this whole process reminds one of the earlier elevation of geometry from empirical knowledge based on experience to a product of pure reason.

One question that naturally and immediately comes to mind is this: How is it that these synthetic a priori's, which are present in advance of experience, nevertheless fit experience so well and efficiently? In effect the question is: If these synthetic truths are not results of experience, where do they really come from? How is it that our minds already possess this machinery which then fits experience so well and precisely? To this there was then no convincing answer, but we come back to it in a moment.

During the nineteenth century the developments in physics reinforced the world view established earlier. There were many new discoveries: electricity and magnetism were seen to be closely related phenomena, and after their unification by Maxwell, the science of light was seen to be a part of electromagnetism. Prior to this, the wave theory of light had come into its own, as against the corpuscular theory advocated by Newton. Also in this process, the concept of the field as an essential ingredient of physics, additional to material substance as particles, was created and understood. The electromagnetic field too carried energy and momentum, and could exchange them with matter. The unification of electricity, magnetism and optics into one scheme was the second great unification in physics, after Newton's universal gravity. All in all, Galilean–Newtonian dynamics on the one hand and the Faraday–Maxwell electromagnetic theory on the other produced a world picture in which natural phenomena took place along strictly deterministic and causal lines, obeying definite mathematical laws; and our minds were presented with a faithful picture of an independent and externally existing real world. Towards the end of the nineteenth century, however, serious faults in the foundations began to show up, which led to the major developments of relativity and quantum theory in this century. On the one hand, an incompatibility between mechanics and electromagnetism was found; this was resolved by special relativity, by modifying mechanics to fall into line with electromagnetism. On the other hand, a serious discrepancy between electromagnetism and classical statistical physics developed, which required the development of quantum theory and pretty much an overhauling of everything at the conceptual level in classical physics! But at this point let us return to the question raised earlier about Kant's philosophical system: If the synthetic a priori's are a priori, why do they fit later experience so well?

The answer comes essentially from biology and the theory of evolution, which makes possible a reinterpretation and revalidation of Kant's ideas. It also tells us why these ideas may be limited, and in a sense prepares us mentally for the surprising and noncommonsensical later developments in physics. The essential point is a proper appreciation of the relative roles of phylogenesis and ontogenesis—the development of the species over many generations and long periods of time, controlled or directed by natural evolution, and the development of each individual organism, each human being, in his or her own lifetime. The argument has been beautifully expressed in a recent book, *Mind from Matter?*, by Max Delbrück. Several distinct ideas are involved: how in the course of evolution of species—phylogenesis—new abilities of organisms arise, and those conducive to survival are retained, just because individuals with those abilities leave more progeny; how infants in their period of growth learn to absorb experience and to deal with their surroundings; and how the mature adult mind manipulates and processes the sensory inputs reaching it from the external world. Our own world of daily experience is called the 'world of middle dimensions'. It is roughly of our own scale in size and duration. From the phylogenetic point of view, organisms capable of dealing successfully with the most important features of *this* world are of course favoured. Among these features are indeed those of identity and permanence of material objects, the ideas of causes for events and an orderly pattern to experience, and geometrical properties of space. Thus the capacity to detect such features in the world of middle dimensions is useful for survival, and this has developed slowly over long periods of biological evolution. Conversely and to the same extent, these are objectively real features of the world at this scale. But this only means that each individual member of the species is born with—or comes equipped with—the capacity to see such aspects of the world around him, or at least completes the development of such capacity in early infancy. The basic lesson is: what is the result of biological evolution, what is a posteriori for the species, *appears to be a priori for the individual.* A posteriori for phylogenesis can lead to the a priori for ontogenesis.

But even here this 'a priori' apparatus is not born ready-made in all details in the infant; during infancy, the innate capabilities provided by phylogenesis must, by experience and exposure to the external world, be made into a workable and reliable system. I can do no better than quote Delbrück *in extenso* at this point:

> It appears therefore that two kinds of learning are involved in our dealing with the world. One is *phylogenetic* learning, in the sense that during evolution we have evolved very sophisticated machinery for perceiving and making inferences about a real world. . . . In other words, whereas in the light of modern understanding of evolutionary processes we can say the individual approaches perception a priori, this is by no means true when we consider the history of mankind as a whole. What is a priori for individuals is a posteriori for the species. The second kind of learning involved in dealing with the world is *ontogenetic* learning, namely the lifelong acquisition of cultural, linguistic and scientific knowledge. Thus we see the world through multiple pairs of glasses: some of them are inherited as part of our physiological apparatus, others acquired from direct experiences as we proceed through life. In a sense, the discoveries of science help us to see what the world is like without some of these pairs of glasses.

Delbrück describes in some detail how the basic notions of the world around us are developed in every child during early infancy through interaction with that world. Thus the identity of a piece of matter, its permanence, the association of causes to events as well as the motivation to always look for them are all slowly learned in the early years from birth onwards. These 'facts' have been obtained through studies in developmental psychology, and it is fascinating to realize that this is how we all grew up! For instance: between birth and two years, infants construct the concepts of object, space and causality; between two and five years, the capacity to use symbols to represent objects and events, and to reason from memory and analogy, all develop; from five to ten years, our minds learn to classify and build hierarchies, and the concepts of continuous quantities like weight and volume, and their conservation, arise; it is between ten and fourteen years that the ability for abstract thinking, logical arguments, assertions and consideration of hypotheses that may or may not be true are built up. Phylogenesis endows us with the innate capacity to develop these attributes and abilities because if we do develop them we are more likely to survive in the world of middle dimensions. This then is the origin of the Kantian a priori categories of thought—thoroughly intertwined with biology in a way Kant could not have foreseen. At the same time, we realize that many seemingly 'obvious' features of the world around us are features we have slowly learned to recognize.

It is amusing to mention here the following sentence from the preface to the book *Principles of Quantum Mechanics* (1930) by Paul Dirac: 'Like the fundamental concepts (e.g. proximity, identity) which everyone must learn on his arrival into the world, the newer concepts of physics can be mastered only by long familiarity with their properties and uses.'

This reinterpretation of Kant could be expressed by saying that—unknowingly—he was far ahead of his time. At the same time, it teaches us that the Kantian synthetic a priori's—introduced by him to justify Galilean–Newtonian physics—are biologically evolved and really appropriate only for the world of middle dimensions.

We must then *not be surprised* if Galilean–Newtonian principles do not extend to the world of the very fast, the very large, or the very small—no surprise if phenomena in these regimes seem to defy intuition! But the truth is that our intuitions are so much a part of us in biological terms that we simply cannot escape them and cannot avoid the feeling of strangeness in dealing with relativity and quantum theory—more so with the latter!

Against this background let us quickly see how the modern developments in physics have led us very far indeed from the world of middle dimensions, to concepts and phenomena that can be accurately described only in mathematical language, and for which ordinary language, pictures and intuition often fail. We are concerned with special relativity, general relativity and quantum theory. The first was essentially completed in 1905; the second was fashioned in the decade 1905–1915; quantum theory took the entire quarter century from 1900 to 1925 and required many talents to complete it. In Newton's physics, space and time were both absolute and mutually independent. In particular, the concept of simultaneity was an absolute one. If one observer declared that two events taking place at two different points in space were simultaneous in time, all others would agree. However special relativity showed that simultaneity of spatially separated events could not be absolute. There is no such thing as a universal present or 'now' with the same meaning for everyone. While for *each* (inertial) observer, space and time retained Newtonian properties, with the former obeying Euclidean geometry and the latter flowing uniformly, two events appearing simultaneous to one observer could very well seem not to be so to another observer. What all observers share is a common space–time, but each one carves out his own separate space and separate time in his own way, not always coinciding with another observer's separation. On the one hand space and time become unified into a greater whole, which alone is the same for everyone; on the other hand, there is a refinement of the terms 'past' and 'future', and which events could be causes for which other events. With respect to mechanics, substance is seen to be a form of energy; and subject to well understood restrictions, matter and radiation are interconvertible.

General relativity takes us one step further away from the intuitive commonsense world of middle dimensions. While special relativity expressed electromagnetism in its proper form, gravity had been left out of the picture. This was resolved by general relativity. The attempt to reconcile special relativity with gravitation led to the former being superseded and giving place to general relativity. Inclusion of gravitation was shown by Einstein to involve changing the geometry of space and of space–time from Euclidean to non-Euclidean types! Thus Euclidean geometry is no longer an a priori product of pure reason which necessarily must be obeyed by nature. The actual geometry of space has physical origins and causes, to be experimentally and empirically determined. Along with the earlier particles and fields, geometry too becomes an ingredient of classical physics, participating in and subject to physical laws.

These movements away from intuitive ideas of simultaneity, causality and Euclidean geometry are things one can get accustomed to with reasonable training and dependence on the appropriate kind of mathematics. However, when we come to quantum mechanics, the changes are considerably more drastic and startling, since now all the intuitive ideas of substance, permanence, identity of objects, determinism and objectivity get affected. To begin with, the two classically distinct categories of particles and fields get fused or amalgamated; particles have wave attributes and vice versa. Matter loses some of its substantiality, solidity and permanence. Since at the microscopic level material points no longer have precisely defined paths in space along which they move, the meaning of similarity or identity of particles acquires a new and much more refined meaning. It also leads to ways in which identical particles can influence one another, which cannot be encompassed in the classical concepts of potential and force. Added to all this, quantum-mechanical laws are statistical or probabilistic in nature, and furthermore they do not allow us to picture an atomic system as existing in some precisely defined state of its own independent of our observations of and experiments on it! Thus both determinism and objectivity are affected and changed from the classical ideals. Even with as complete knowledge as is in principle permitted by quantum mechanics at a given time of an atomic system, we are only able to make probabilistic predictions about what might happen when we measure some quantity or the other at a later time! One cannot consistently imagine that a microscopic physical system exists by itself with definite numerical properties of its own, which our observations then reveal to us. According to the conventional interpretation, an experiment to measure a physical property always causes some disturbance to the system, and the result of the measurement is brought about by the measurement and was not pre-existing. Things do not have values in advance of measurement, and all things cannot simultaneously be measured or have values. To borrow Heisenberg's expression, potentiality (not as probability but as probability amplitude) rather than actuality is the fundamental quantity in quantum mechanics and is subject to a definite law of evolution in time. Such conceptions are what make quantum mechanics so counter-intuitive and hard to swallow; one is forbidden to make a mental picture of a system as existing on its own. To quote Paul Dirac at this point, the fundamental laws of nature 'control a substratum of which we cannot form a mental picture without introducing irrelevancies'. Here of course we relate what we mean by intuition, commonsense, and the desire to picture an external world independent of ourselves all to our biological heritage, our phylogeny! We need such a model or picture at least of the world of middle dimensions so that we can evolve strategies to deal with it and survive in it.

We thus see that each one of the intuitive features of the world around us that we have painstakingly grasped through a combination of phylogenesis and ontogenesis has been superseded or sacrificed by later developments in physics when we study the very fast, the very large, or the very small. The commonsense notions of substance, identity, permanence, objects, causality, determinism and geometry so assiduously learnt in infancy—the capacity to learn having been inherited—and so suited to the world of middle dimensions, have to be altered in dealing with other dimensions! One may be struck by the fact that in so many essential respects we have had to go beyond commonsense understanding, but maybe if we had not, that too would have been a riddle to be explained. This exploration of nature far from our own scale is well described by Schwinger:

> It is remarkable how Nature aids mankind's groping toward an understanding of the universe. As we raise the level of our scientific skills and sharpen our artificial senses, fascinating new phenomena continue to appear, testing and challenging our growing comprehension of Nature's grand design.

One of the key ingredients in the conventional interpretation of quantum mechanics is the principle of complementarity due to Niels Bohr. There are two aspects, both relevant here. The first is that for microscopic systems, every experimental arrangement and observation leading to some result cannot be dissociated from that result. As we said earlier, we cannot take the attitude that the result represents something that the system already possessed, and which our measurement merely revealed. In quantum mechanics, according to complementarity, experimental apparatus and result obtained must be kept together as a whole and not split apart. But then the experimental set-ups needed to measure two different physical properties may very well be mutually exclusive, and get in each other's way! In that case we say these properties form a complementary pair: knowledge of one leads to renouncing the possibility of simultaneous knowledge of the other. Position and momentum of an electron are an example of complementary variables. So are the phase and the number of photons in an electromagnetic wave.

This fundamental principle governing atomic phenomena led Niels Bohr to suggest in 1932 that it may have implications for the understanding of life too. If we want to understand the functioning of a cell in terms of physics and chemistry and at the atomic level, the experimental technique needed would be such as to kill the cell. Therefore the property of life and understanding cell functions in terms of quantum mechanics may be mutually exclusive or complementary. This led to his suggestion that the understanding of life would require something beyond quantum mechanics and yet to be discovered, not within quantum mechanics itself.

These views of Niels Bohr had the effect of inducing Max Delbrück to turn from theoretical physics to molecular biology. Delbrück essentially made the attempt to see whether Bohr's idea was necessary to understand life processes. In his book referred to earlier, Delbrück describes the attempt and comes to the conclusion—like some others before him—that the principle of complementarity is not necessary in this context, and the situation is actually conceptually much simpler. To quote him,

> It might be said that Watson and Crick's discovery of the DNA double helix in 1953 did for biology what many physicists had hoped in vain could be done for atomic physics: it solved all the mysteries in terms of classical models and theories, without forcing us to abandon our intuitive notions about truth and reality.

However, on this question I must mention that recently Brian Josephson has argued that Bohr's suggestion is indeed relevant to the understanding of life, and that there are limits to the applicability of quantum mechanics. His argument rests on the different roles of the disturbance due to measurement in physical systems on the one hand and living systems on the other.

Now let us return to the problems of interpreting quantum mechanics. As mentioned earlier, an important statement is that an atomic system has no numerical properties of its own unless and until it is subject to experiment and observation. This has led to the idea that an external consciousness—of the experimenter and observer—is an essential part of the whole scheme of quantum mechanics. Many leading physicists have refused to accept such a situation; others have taken it as unavoidable. To illustrate the situation I would like to quote from several serious physicists who represent various shades of opinion on this subject, many of whom also express genuine uneasiness about this state of affairs. At one extreme we have

John Wheeler, a close associate of Bohr, who says:

> We used to think of a universe where we could in effect look at stars and galaxies as if it were from behind the safeness of a foot-thick slab of plate glass without getting involved. Today in our own time we have learned that even if we study so minuscule an object as a photon or an electron, in effect we have to smash this slab of glass. We have to reach in and install some kind of measuring equipment, and according as we set that equipment to measure one aspect of the situation or another, we get different results. We simply cannot put both pieces of equipment in at the same time; we have to make the choice. And what's more, what choice we make has an irretrievable influence on what will happen from then on. We have been promoted from observers to participators. There is a strange sense in which this is a participatory universe.

But his hesitation is also evident in the words, 'I confess that sometimes I do take 100 per cent seriously the idea that the world is a figment of the imagination and, other times, that the world does exist out there independent of us.'

In contrast, at the other extreme, is Einstein's well-known statement, 'The belief in an external world independent of the perceiving subject is the basis of all natural science.'

A kind of in-between attitude is reflected by Heisenberg:

> To what extent, then, have we finally come to an objective description of the world, especially of the atomic world? In classical physics science started from the belief . . . that we could describe the world or at least parts of the world without any reference to ourselves. This is actually possible to a large extent. . . . One may perhaps say that quantum theory corresponds to this ideal as far as possible. . . . We have to remember that what we observe is not nature in itself but nature exposed to our method of questioning. Our scientific work in physics consists in asking questions about nature in the language that we possess and trying to get an answer from experiment by the means that are at our disposal. . . . It is understandable that in our scientific relation to nature our own activity becomes very important when we have to deal with parts of nature into which we can penetrate only by using the most elaborate tools.

This problem of consciousness concerned Erwin Schrödinger too a great deal. The striking fact is that through study of inanimate atomic systems one should have come to a stage where one has to commit oneself on such problems as existence of consciousness prior to understanding of atomic phenomena. Speaking on the evolution of consciousness in *Mind and Matter*, he asks:

> Are we prepared to believe that this very special turn in the development of the higher animals, a turn that might after all have failed to appear, was a necessary condition for the world to flash up to itself in the light of consciousness? Would it otherwise have remained a play before empty benches, not existing for anybody, thus, quite properly speaking, not existing? This would seem to me the bankruptcy of a world picture.

Later in the same essay, speaking of the emergence of the brain in certain animals alone, he says: 'Only a small fraction of them (if you count by species) have embarked on "getting themselves a brain". And before that happened, should it all have been a performance to empty stalls?' Actually, Schrödinger was never happy with the conventional interpretation of quantum mechanics. Nonetheless, from such passages it should at least be understandable to a biologist why a serious study of quantum mechanics would tempt one to make definite statements about the nature of consciousness, the need for its existence as viewed from physical science practically amounting to an assertion that there are reasons from outside biology why consciousness should exist.

These days, with the many startling discoveries of the way the brain (human or animal) functions, there is a great deal of caution in dealing with mind versus brain, consciousness, etc. The brain is an incredibly complex piece of machinery; and unlike what might have been previously imagined, the nervous system does not 'present' to it a 'faithful image' of an objective external world. Studies of the visual system, for instance, have shown that while the eye lens and retina function optically pretty much like a camera, thereafter an enormous amount of processing of the visual input is performed by the brain. The optical information is broken up into bits and pieces and sent to different cells in that part of the brain concerned with vision. Some cells are sensitive to patterns of contrasting illumination in one direction, some in another; other cells react only if something in the scene moves; and so on and so forth. These different aspects or features of the external visual scene are 'picked up' by different, spatially somewhat separated cells in the visual cortex. Aside from asking the obvious question—when, how and 'by whom' is it all put together again—one is definitely struck by the complexity of the entire operation. It is not even the case that one is equipped at birth with all these capacities, but that in a few critical periods in early infancy, the wiring of the machinery and testing it are completed while interacting with the environment. Deprivation of this interaction at crucial times can lead to drastic deficiencies in the adult individual. Thus the way the brain perceives the world is by a complex series of filters and processing operations—not through a naive, faithful image, but a highly treated one. The idea of 'naive realism' is here replaced by 'structuralist realism' to reflect this fact. To a physicist, this is a fine example of capacity being turned into actuality—the interplay of phylogenesis and ontogenesis. Thus, all in all, the picture of external reality that is ultimately available to the brain is a highly filtered and processed one, involving many intricate steps on the way.

Those who have made these discoveries (and others too) are naturally very greatly impressed by the complexity of brain functioning. Their reaction to any attempt to discuss consciousness from the physicist's perspective is generally to say: wait, we do not yet know even how to define the term properly; let us go on with our studies on how the brain works and unravel all its details; and in good time the understanding of consciousness and mind may come out automatically. To quote Delbrück:

> The point of view of the evolutionist forces us to view mind in the context of other aspects of evolution, to draw parallels with other, more mundane forms of adaptation, such as the organs of locomotion and of digestion. In the context of evolution, the mind of the adult human, the object of so many centuries of philosophical studies, ceases to be a mysterious phenomenon, a thing into itself. Rather, mind is seen to be an adaptive response to selective pressures, just as is nearly everything else in the living world.

One question that Delbrück does not seem to convincingly answer, though, is why the brain is capable of so much more than would seem necessary for survival. Anyway physicists are a bit impatient, being faced by problems of their own, and do not want to be deterred by such warnings. In Schrödinger's words, 'The urge to find a way out of this impasse ought not to be damped by the fear of incurring the wise rationalist's mockery.'

Is biology then going to be a part of physics, just as chemistry? Certainly in Delbrück's view, as quoted earlier, the understanding of life is going to be easier and less subtle than the mysteries of quantum mechanics; it will not require our giving up our intuitive notions of reality. But reality in quantum mechanics is different from the classical conception, more subtle than naive objectivity. Let me conclude by presenting the views of a very highly respected physicist, Rudolph Peierls. In discussing the question of the prior need for consciousness in setting up quantum measurement theory, he says:

> This question seems to pose an insurmountable difficulty. But it is based on the assumption that living beings . . . can be described by the existing laws of physics, in other words, that biology is ultimately a branch of physics in the sense in which chemistry is now known to be, in principle, a branch of physics. . . . Many people take it for granted that the same must be true of the science of life. The difficulty about how to formulate the acquisition of information . . . is a strong reason for doubting this assumption. This is not far from the question of how one would incorporate the concept of consciousness into a description of living beings in terms of the physical functioning of their brain cells. Consciousness is admittedly hard to define objectively, but each of us has a clear, intuitive understanding of what he means by being conscious. . . . In claiming that biology is not likely to be a branch of the present physics, I do not wish to imply that life can in some mysterious way evade the laws of physics. . . . It is at least possible, and to me probable, that . . . new concepts have to be added to our present physical ones before an adequate description of life is possible. Whether the thus enlarged discipline should still be called physics is a semantic question.

May I leave you with these thoughts, fully conscious that at best my puzzlement has been transmitted to you. The physics–biology relationship could have been discussed from other points of view too—nonequilibrium thermodynamics, microscopic molecular structure, etc.—but a particular one was chosen. At least this facet of the problem would have been brought home to you.

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